

1 DETERMINING RESISTIVITY OF A FORMATION
2 ADJACENT TO A BOREHOLE HAVING CASING
3 WITH AN APPARATUS HAVING ALL CURRENT
4 CONDUCTING ELECTRODES WITHIN THE CASED WELL
5
6

7 This application is a Continuation-in-Part Application
8 of a Divisional Application that is entitled "Determining
9 Resistivity of a Formation Adjacent to a Borehole Having
10 Casing by Generating Constant Current Flow in Portion of
11 Casing and Using at Least Two Voltage Measurement
12 Electrodes"; which is Serial No. 08/738,924; which has the
13 filing date of 10/28/1996; and which is to issue shortly as
14 a U.S. Patent. An entire copy of Serial No. 08/738,924 is
15 included herein by reference.
16

17 Serial No. 08/738,924 is a Divisional Application of
18 a Continuation-in-Part Application that is entitled
19 "Determining Resistivity of a Formation Adjacent to a
20 Borehole Having Casing Using Multiple Electrodes and With
21 Resistances Being Defined Between the Electrodes"; which is
22 Serial No. 08/083,615; which has the filing date of 6/28/93;
23 and which issued on 10/29/96 as U.S. Patent No. 5,570,024
24 {"Vail(024)"}. An entire copy of Serial No. 08/083,615 is
25 included herein by reference.
26

27 Serial No. 08/083,615 is a Continuation-in-Part
28 Application of an earlier Divisional Application that
29 is entitled "Methods of Operation of Apparatus Measuring
30 Formation Resistivity From Within a Cased Well Having One
31 Measurement and Two Compensation Steps"; which is Serial
32 No. 07/754,965; which has the filing date of 9/4/1991; and
33 that issued on 6/29/1993 as U.S. Patent No. 5,223,794
34

1 {"Vail(794)"}. A entire copy of Serial No. 07/754,965 is
2 included herein by reference.

3
4 Serial No. 07/754,965 is a Divisional Application of an
5 earlier Continuation-in-Part Application that is entitled
6 "Electronic Measurement Apparatus Movable In a Cased Borehole
7 and Compensating for Casing Resistance Differences"; which is
8 Serial No. 07/434,886; which has the filing date of
9 11/13/1989; and which issued on 12/24/1991 as U.S. Patent
10 No. 5,075,626 {"Vail(626)"}. An entire copy of Serial
11 No. 07/434,886 is included herein by reference.

12
13 Serial No. 07/434,886 is a Continuation-in-Part
14 Application of an earlier Continuation-in-Part Application
15 having the title of "Methods and Apparatus for Measurement of
16 Electronic Properties of Geological Formations Through
17 Borehole Casing"; which is Serial No. 07/089,697; which has
18 the filing date of 08/26/1987; and which issued on 11/21/1989
19 as U.S. Patent No. 4,882,542 {"Vail(542)"}. An entire copy
20 of Serial No. 07/089,697 is included herein by reference.

21
22 Serial No. 07/089,697 is a Continuation-in-Part
23 Application of the original Parent Application having the
24 title "Methods and Apparatus for Measurement of the
25 Resistivity of Geological Formations from Within Cased
26 Boreholes"; which is Serial No. 06/927,115; which has the
27 filing date of 11/4/1986; and which issued on 4/11/1989
28 as U.S. Patent No. 4,820,989 {"Vail(989)"}. An entire copy
29 of Serial No. 06/927,115 is included herein by reference.

30
31 The above paragraphs define a total of 5 issued U.S.
32 Patents, and 1 co-pending U.S. Patent Application, that
33 show the "direct chain" of applications leading to the
34 application herein.

1 However, there are an additional 5 U.S. Patents that
2 have issued that are related to this application. In
3 addition, there are yet 2 more U.S. Patent Applications that
4 are co-pending in the USPTO that are related to this case.
5 These are defined in the following, respectively enumerated
6 as (i), (ii), (iii), (iv), (v), (vi) and (vii).
7

8 (i) U.S. Patent No. 5,043,669 {"Vail(669)"} entitled
9 "Methods and Apparatus for Measurement of the Resistivity of
10 Geological Formations From Within Cased Wells in Presence of
11 Acoustic and Magnetic Energy Sources"; that issued on
12 8/27/1991; that is Serial No. 07/438,268; that has the
13 filing date of 11/16/1989; and that is a Continuation-in-Part
14 Application of Serial No. 07/089,697. An entire copy of
15 Serial No. 07/438,268 is included herein by reference.
16

17 (ii) U.S. Patent No. 5,043,668 {"Vail(668)"} entitled
18 "Methods and Apparatus for Measurement of Electronic
19 Properties of Geological Formations Through Borehole Casing";
20 that issued on 8/27/1991; that is Serial No. 07/435,273; that
21 has the filing date of 10/30/1989; and that is a Continuation
22 Application of Serial No. 07/089,697. An entire copy of
23 Serial No. 07/435,273 is included herein by reference.
24

25 (iii) U.S. Patent No. 5,187,440 {"Vail(440)"} entitled
26 "Measuring Resistivity Changes From Within a First Cased Well
27 to Monitor Fluids Injected Into Oil Bearing Geological
28 Formations From a Second Cased Well While Passing Electrical
29 Current Between the Two Cased Wells"; that issued on
30 2/16/1993; that is Serial No. 07/749,136; that has the filing
31 date of 8/23/1991; and that is a Continuation-in-Part
32 Application of Serial No. 07/435,273. An entire copy of
33 Serial No. 07/749,136 is included herein by reference.
34

1 (iv) U.S. Patent No. 5,633,590 {"Vail(590)"} entitled
2 "Formation Resistivity Measurements from Within a Cased Well
3 Used to Quantitatively Determine the Amount of Oil and Gas
4 Present"; that issued on 5/27/1997; that is Serial
5 No. 08/214,648; that has the filing date of 3/17/1994;
6 and that is a Continuation-in-Part Application of Serial
7 No. 08/083,615. An entire copy of Serial No. 08/214,628
8 is included herein by reference.
9

10 (v) U.S. Patent No. 5,717,334 {"Vail(334)"} entitled
11 "Methods and Apparatus to Produce Stick-Slip Motion of
12 Logging Tool Attached to a Wireline Drawn Upward by a
13 Continuously Rotating Wireline Drum"; that issued on
14 2/10/1998; that is Serial No. 08/508,781; that has the filing
15 date of 7/28/1995; that is a Continuation-in-Part Application
16 of Serial No. 08/083,615. An entire copy of Serial
17 No. 08/508,781 is included herein by reference.
18

19 (vi) Co-pending application Serial No. 08/685,796
20 entitled "Electrical Voltages and Resistances Measured to
21 Inspect Metallic Cased Wells and Pipelines"; that has the
22 filing date of 7/23/1996; that is an FWC Application of
23 Serial No. 08/271,869 (now abandoned); and Serial
24 No. 08/271,869 is a Continuation-in-Part Application
25 of Serial No. 08/083,615. An entire copy of Serial
26 No. 08/685,796 is included herein by reference.
27

28 (vii) Co-pending application Serial No. 08/864,309
29 entitled "Formation Resistivity Measurements from Within a
30 Cased Well Used to Quantitatively Determine the Amount of Oil
31 and Gas Present"; that has the filing date of 5/27/1997; that
32 is a Continuation Application of Serial No. 08/214,648.
33 An entire copy of Serial No. 08/864,309 is included herein
34 by reference.

1 The Office Action for Serial No. 08/738,924 made
2 by Examiner Walter E. Snow, Primary Examiner, that was mailed
3 on the date of 9/21/1998, had attached to it a total of seven
4 sheets of Form PTO-1449 specifically including: sheets 1-5
5 having the stamp of "OIPE OCT 26 1997"; sheet 1 having the
6 stamp of "OIPE JUL 25 1998"; and sheet 1 having the stamp
7 of "OIPE AUG 05 1996"; which seven total sheets are included
8 herein by their entirety by reference. Further, each and
9 every reference cited on those seven sheets, namely,
10 references AA-AV; BA-BE; CA-DO; EA-EC; and FA-FC; are
11 included herein in their entirety by reference. Therefore,
12 included herein by reference in their entirety is each and
13 every one of those 74 references cited in the previous
14 sentence.

15
16 Portions of this application have been disclosed in U.S.
17 Disclosure Document No. 228495, filed June 5, 1989, an entire
18 copy of which is included herein by reference. Other U.S.
19 Disclosure Documents related to this application have been
20 filed in the USPTO, and entire copies of all of those
21 U.S. Disclosure Documents are included herein by reference
22 (and those U.S. Disclosure Document numbers shall be provided
23 by applicant in a later amendment to be filed by applicant).

24
25 This invention was made with Government support under
26 DOE Grant No. DE-FG06-84ER13294, entitled "Validating the
27 Paramagnetic Logging Effect", Office of Basic Energy
28 Sciences, of the U.S. Department of Energy. The government
29 has certain rights in this invention. The basic concept for
30 the invention described herein was conceived during the
31 funding provided by the above grant.

32
33 Ongoing research to measure resistivity through
34 casing has been provided on a co-funded basis from:

1 (a) U.S. Department of Energy Grant No. DE-FG19-88BC14243
2 entitled "Proof of Feasibility of Thru Casing Resistivity
3 Technology"; (b) U.S. Department of Energy (DOE) Grant
4 No. DE-FG22-90BC14617 entitled "Proof of Concept of Moving
5 Thru Casing Resistivity Apparatus"; (c) U.S. Department of
6 Energy Grant No. DE-FG22-93BC14966 entitled "Fabrication and
7 Downhole Testing of Moving Through Casing Resistivity
8 Apparatus"; and (d) Gas Research Institute (GRI) Contract
9 No. 5088-212-1664 entitled "Proof of Feasibility of the
10 Through Casing Resistivity Technology". The government
11 and the GRI have certain rights in this invention.
12

13 This invention provides improved methods and apparatus
14 for measurement of the electronic properties of formations
15 such as the resistivities, polarization phenomena, and
16 dielectric constants of geological formations and cement
17 layers adjacent to cased boreholes and for measuring the skin
18 effect of the casing present. The terms "electronic
19 properties of formations" and "electrochemical properties of
20 formations" are used interchangeably herein.
21

22 The oil industry has long sought to measure resistivity
23 through casing. Such resistivity measurements, and
24 measurements of other electrochemical phenomena, are useful
25 for at least the following purposes: locating bypassed oil
26 and gas; reservoir evaluation; monitoring water floods;
27 measuring quantitative saturations; cement evaluation;
28 permeability measurements; and measurements through a drill
29 string attached to a drilling bit. Therefore, measurements
30 of resistivity and other electrochemical phenomena through
31 metallic pipes, and steel pipes in particular, are an
32 important subject in the oil industry. Many U.S. patents
33 have issued in the pertinent Subclass 368 of Class 324 of the
34 United States Patent and Trademark Office which address this

1 subject. The following presents a brief description of the
2 particularly relevant prior art presented in the order of
3 descending relative importance.

4
5 U.S. Patents which have already issued to the inventor
6 in the is field are listed as follows:

7 U.S. Patent No. 4,820,989 (Serial No. 06/927,115);
8 U.S. Patent No. 4,882,542 (Serial No. 07/089,697);
9 U.S. Patent No. 5,043,668 (Serial No. 07/435,273);
10 U.S. Patent No. 5,043,669 (Serial No. 07/438,268);
11 U.S. Patent No. 5,075,626 (Serial No. 07/434,886);
12 U.S. Patent No. 5,187,440 (Serial No. 07/749,136);
13 U.S. Patent No. 5,223,794 (Serial No. 07/754,965);
14 U.S. Patent No. 5,570,024 (Serial No. 08/083,615);
15 U.S. Patent No. 5,633,590 (Serial No. 08/214,648); and
16 U.S. Patent No. 5,717,334 (Serial No. 08/508,781).

17
18 As of the filing date of the application herein, the
19 inventor's currently co-pending U.S. Patent Applications
20 in this field are listed as follows:

21 Serial No. 08/738,924 that is to issue shortly;
22 Serial No. 08/685,796 that is to also issue shortly; and
23 Serial No. 08/864,309 that is co-pending with the
24 application herein.

25
26 The above 10 issued U.S. Patents, and any of the
27 additional cases when they issue, are collectively identified
28 as "the Vail Patents" for the purposes herein. For the
29 record, entire copies of each and every one of the above 13
30 cases identified by serial number are included herein in
31 their entirety by reference.

32
33 The apparatus and methods of operation herein disclosed
34 are embodiments of the Through Casing Resistivity Tool® that

1 is abbreviated TCRT®. The Through Casing Resistivity Tool®
2 and TCRT® are Trademarks of ParaMagnetic Logging, Inc. in the
3 United States Patent and Trademark Office.
4

5 An important publication concerning the Through Casing
6 Resistivity Tool (TCRT) and the Vail Patents is the article
7 entitled "Formation Resistivity Measurements Through Metal
8 Casing", having authors of W.B. Vail and S.T. Momii of
9 ParaMagnetic Logging, Inc., R. Woodhouse of Petroleum and
10 Earth Science Consulting, M. Alberty and R.C.A. Peveraro of
11 BP Exploration, and J.D. Klein of Arco Exploration and
12 Production Technology, which appeared as Paper "F", Volume I,
13 in the Transactions of the SPWLA Thirty-Fourth Annual Logging
14 Symposium, Calgary, Alberta, Canada, June 13-16, 1993,
15 sponsored by The Society of Professional Well Log Analysts,
16 Inc. of Houston, Texas and the Canadian Well Logging Society
17 of Calgary, Alberta, Canada (13 pages of text and
18 8 additional figures); an entire copy of which is included
19 herein by reference. Experimental results are presented
20 therein which confirm that the apparatus and methods
21 disclosed the Vail Patents actually work in practice to
22 measure the resistivity of geological formations adjacent to
23 cased wells. To the author's knowledge, this SPWLA paper
24 presents the first accurate measurements of resistivity
25 obtained from within cased wells using any previous
26 experimental apparatus.
27

28 Another important publication related to the Vail
29 Patents is the article entitled "Formation Resistivity
30 Measurements Through Metal Casing at the MWX-2 Well in Rifle,
31 Colorado", having the authors of W.B. Vail and S.T. Momii of
32 ParaMagnetic Logging, Inc., H. Haines of Gas Research
33 Institute, J.F. Gould, Jr. of Mobil Exploration & Producing
34 U.S., and W.D. Kennedy of the Mobil Research and Development

1 Corporation, which appeared as Paper "OO" in the SPWLA 36th
2 Annual Logging Symposium, Paris, France, June 26-29, 1995,
3 Sponsored by The Society of Professional Well Log Analysts,
4 Inc., 12 pages including Figures 1-5, an entire copy of which
5 is included herein by reference.
6

7 Yet another important publication related to the Vail
8 Patents is the article entitled "Through Casing Resistivity
9 Measurements and Their Interpretation for Hydrocarbon
10 Saturations", having the authors of W.B. Vail and S.T. Momii
11 of ParaMagnetic Logging, Inc., and J.T. Dewan of Dewan &
12 Timko, Inc., that is SPE Paper 30582, presented at the SPE
13 Annual Technical Conference & Exhibition, Dallas, Texas,
14 October 22-26, 1995, pages 533-548, including Figures 1-18,
15 an entire copy of which is included herein by reference.
16

17 Yet another important publication related to the Vail
18 Patents is the article entitled "Through Casing Resistivity
19 Tool™ To Locate Bypassed Oil", having the authors of
20 W. Banning Vail, Steven T. Momii, and Richard Woodhouse, that
21 appeared in The American Oil & Gas Reporter, October, 1995,
22 pages 70-76, including Figures 1-3, an entire copy of which
23 is included herein by reference.
24

25 And yet another extensive publication related to the
26 Vail Patents is the document entitled "Proof of Feasibility
27 of the Through Casing Resistivity Technology", that is the
28 Final Report to Gas Research Institute for research work
29 performed from the dates of April 1988 to March 1994 under
30 GRI Contract No. 5088-212-1664, having the authors of
31 W.B. Vail and S.T. Momii of ParaMagnetic Logging,
32 March, 1996, having a total of 328 pages and 169 figures, an
33 entire copy of which is included herein by reference. This
34 Final Report dated March, 1996 is a revised version of an

1 earlier document entitled "First Draft of the Final Report to
2 GRI" and dated July 4, 1994, an entire copy of which is also
3 incorporated herein by reference.
4

5 The Vail Patents describe the various embodiments of the
6 Through Casing Resistivity Tool® (TCRT®). Many of these Vail
7 Patents describe embodiments of apparatus having three or
8 more spaced apart voltage measurement electrodes which engage
9 the interior of the casing, and which also have calibration
10 means to calibrate for thickness variations of the casing and
11 for errors in the placements of the voltage measurement
12 electrodes.
13

14 U.S. Patent No. 4,796,186 which issued on January 3,
15 1989 to Alexander A. Kaufman entitled "Conductivity
16 Determination in a Formation Having a Cased Well" also
17 describes apparatus having three or more spaced apart voltage
18 measurement electrodes which engage the interior of the
19 casing and which also have calibration means to calibrate for
20 thickness variations in the casing and for errors in the
21 placements of the electrodes. This patent has been assigned
22 to ParaMagnetic Logging, Inc. of Woodinville, Washington.
23 In general, different methods of operation and analysis are
24 described in the Kaufman Patent compared to the Vail Patents
25 cited above.
26

27 U.S. Patent No. 4,837,518 which issued on June 6, 1989
28 to Michael F. Gard, John E. E. Kingman, and James
29 D. Klein, assigned to the Atlantic Richfield Company,
30 entitled "Method and Apparatus for Measuring the Electrical
31 Resistivity of Geologic Formations Through Metal Drill Pipe
32 or Casing", predominantly describes two voltage measurement
33 electrodes and several other current introducing electrodes
34 disposed vertically within a cased well which electrically

1 engage the wall of the casing, henceforth referenced as "the
2 Arco Patent". However, the Arco Patent does not describe an
3 apparatus having three spaced apart voltage measurement
4 electrodes and associated electronics which takes the voltage
5 differential between two pairs of the three spaced apart
6 voltage measurement electrodes to directly measure electronic
7 properties adjacent to formations. Nor does the Arco Patent
8 describe an apparatus having at least three spaced apart
9 voltage measurement electrodes wherein the voltage drops
10 across adjacent pairs of the spaced apart voltage measurement
11 electrodes are simultaneously measured to directly measure
12 electronic properties adjacent to formations. Therefore, the
13 Arco Patent does not describe the methods and apparatus
14 disclosed herein.

15
16 USSR Patent No. 56,026, which issued on November 30,
17 1939 to L. M. Alpin, henceforth called the "Alpin Patent",
18 which is entitled "Process of the Electrical Measurement of
19 Well Casings", describes an apparatus which has three spaced
20 apart voltage measurement electrodes which positively engage
21 the interior of the casing. However, the Alpin Patent does
22 not have any suitable calibration means to calibrate for
23 thickness variations of the casing nor for errors related to
24 the placements of the voltage measurement electrodes.
25 Therefore, the Alpin Patent does not describe the methods and
26 apparatus disclosed herein.

27
28 French Patent No. 2,207,278 having a "Date of Deposit"
29 of November 20, 1972 (hereinafter "the French Patent")
30 describes apparatus having four spaced apart voltage
31 measurement electrodes which engage the interior of borehole
32 casing respectively defined as electrodes M, N, K, and L.
33 Various uphole and downhole current introducing electrodes
34 are described. Apparatus and methods of operation are

1 provided that determines the average resistance between
2 electrodes M and L. This French Patent further explicitly
3 assumes an exponential current flow along the casing.
4 Voltage measurements across pair MN and KL are then used to
5 infer certain geological parameters from the assumed
6 exponential current flow along the casing. However, the
7 French Patent does not teach measuring a first casing
8 resistance between electrodes MN, does not teach measuring a
9 second casing resistance between electrodes NK, and does not
10 teach measuring a third casing resistance between electrodes
11 KL. The invention herein and other preferred embodiments
12 described in the Vail Patents teach that it is of importance
13 to measure said first, second, and third resistances to
14 compensate current leakage measurements for casing thickness
15 variations and for errors in placements of the voltage
16 measurement electrodes along the casing to provide accurate
17 measurements of current leakage into formation. Further,
18 many embodiments of the Vail Patents do not require any
19 assumption of the form of current flow along the casing to
20 measure current leakage into formation. Therefore, for these
21 reasons alone, the French Patent does not describe the
22 methods and apparatus disclosed herein. There are many other
23 differences between various embodiments of the Vail Patents
24 and the French Patent which are described in great detail in
25 the Statement of Prior Art for Serial No. 07/754,965 dated
26 December 2, 1991 that issued as U.S. Patent No. 5,223,794
27 on June 29, 1993.

28
29 An abstract of an article entitled "Effectiveness of
30 Resistivity Logging of Cased Wells by A Six-Electrode Tool"
31 by N.V. Mamedov was referenced in TULSA ABSTRACTS as follows:
32 "IZV.VYSSH.UCHEB, ZAVEDENII, NEFT GAZ no.7, pp. 11-15, July
33 1987. (ISSN 0445-0108; 5 refs; in Russian)", hereinafter the
34 "Russian Article". It is the applicant's understanding from

1 an English translation of that Russian Article that the
2 article itself mathematically predicts the sensitivity of the
3 type tool described in the above defined French Patent. The
4 Russian Article states that the tool described in the French
5 Patent will only be show a "weak dependence" on the
6 resistivity of rock adjacent to the cased well. By contrast,
7 many embodiments of the Vail Patents, and the invention
8 herein, provide measurements of leakage current and other
9 parameters which are strongly dependent upon the resistivity
10 of the rock adjacent to the cased well. Therefore, this
11 Russian Article does not describe the methods and apparatus
12 disclosed herein.

13
14 U.S. Patent No. 2,729,784, issued on January 3, 1956
15 having the title of "Method and Apparatus for Electric Well
16 Logging", and U.S. Patent No. 2,891,215 issued on June 16,
17 1959 having the title of "Method and Apparatus for Electric
18 Well Logging", both of which issued in the name of Robert
19 E. Fearon, henceforth called the "Fearon Patents", describe
20 apparatus also having two pairs of voltage measurement
21 electrodes which engage the interior of the casing. However,
22 an attempt is made in the Fearon Patents to produce a
23 "virtual electrode" on the casing in an attempt to measure
24 leakage current into formation which provides for methods and
25 apparatus which are unrelated to the Kaufman and Vail Patents
26 cited above. The Fearon Patents neither provide calibration
27 means, nor do they provide methods similar to those described
28 in either the Kaufman Patent or the Vail Patents, to
29 calibrate for thickness variations and errors in the
30 placements of the electrodes. Therefore, the Fearon Patents
31 do not describe the methods and apparatus disclosed herein.

32
33 Accordingly, an object of the invention is to provide
34 new and practical apparatus having three or more spaced apart

1 voltage measurement electrodes to measure formation
2 resistivity from within cased wells.

3
4 It is yet another object of the invention is to provide
5 new methods of operation of the multi-electrode apparatus to
6 measure formation from within cased wells which compensates
7 for casing resistance differences and which compensates for
8 errors in placements of the voltage measurement electrodes.

9
10 And it is yet another object of the invention to provide
11 an apparatus, and suitable methods of operation, to determine
12 the resistivity of a formation adjacent to a borehole having
13 casing with an apparatus having all current conducting
14 electrodes located within the cased well.

15
16 Figure 1 is a sectional view of one preferred embodiment
17 of the invention of the Through Casing Resistivity Tool
18 (TCRT) which is marked with the legend "Prior Art".

19
20 Figure 2 shows ΔI vs. Z which diagrammatically depicts
21 the response of the tool to different formations which is
22 marked with the legend "Prior Art".

23
24 Figure 3 is a sectional view of a preferred embodiment
25 of the invention which shows how V_o is to be measured that is
26 marked with the legend "Prior Art".

27
28 Figure 4 is a sectional view of an embodiment of the
29 invention which has voltage measurement electrodes which are
30 separated by different distances that is marked with the
31 legend "Prior Art".

32
33 Figure 5 is a sectional view of an embodiment of the
34 invention which has electrodes which are separated by

1 different distances and which shows explicitly how to measure
2 V_0 that is marked with the legend "Prior Art".
3

4 Figure 6 is a sectional view of an embodiment of the
5 invention which provides multi-frequency operation to
6 compensate for errors of measurement marked with the legend
7 "Prior Art".
8

9 Figure 7 is a sectional view of an embodiment of the
10 invention that eliminates the use of a certain differential
11 amplifier.
12

13 Figure 8 is a sectional view of an embodiment of the
14 invention that possesses four spaced apart voltage
15 measurement electrodes.
16

17 Figure 9 is a sectional view of an embodiment of the
18 invention that possesses four spaced apart voltage
19 measurement electrodes and extra current introducing
20 electrodes.
21

22 Figure 10 is a multi-electrode apparatus designed to
23 keep certain currents flowing along the casing constant in
24 amplitude in the vicinity of four spaced apart voltage
25 measurement electrodes used to measure resistivity.
26

27 Figure 11 is a multi-electrode apparatus designed to
28 keep certain currents flowing along the casing constant in
29 amplitude in the vicinity of three spaced apart voltage
30 measurement electrodes used to measure resistivity.
31

32 Figure 12 is an apparatus having three spaced apart
33 voltage measurement electrodes and extra current introducing
34 electrodes.

1 Figure 13 is functionally identical to Figure 26 from
2 Serial No. 07/089,697 that is U.S. Patent No. 4,882,542,
3 showing an apparatus having multiple voltage measurement
4 electrodes engaging the interior of the casing that is marked
5 with the legend "Prior Art".
6

7 Figure 14 is identical to Figure 24 from Serial
8 No. 07/089,697 that is U.S. Patent No. 4,882,542 that shows
9 an apparatus for determining the resistivity of a formation
10 adjacent to a borehole having casing wherein all current
11 conducting electrodes are located within the cased well
12 when element 22 is connected through SW1C to electrode B₁.
13 It is marked with the legend "Prior Art".
14

15 The invention is described in three major different
16 portions of the specification. In the first major portion of
17 the specification, relevant parts of the text in Serial
18 No. 07/089,697 {Vail(542)} are repeated herein which describe
19 apparatus defined in Figures 1, 3, 4, and 5. The second
20 major portion of the specification quotes relevant parts of
21 Serial No. 07/434,886 {Vail(626)} that describe the apparatus
22 defined in Figure 6. The third major portion of the
23 specification herein is concerned with providing multi-
24 electrode apparatus and methods of operation of the multi-
25 electrode apparatus to measure formation resistivity from
26 within cased wells that compensates for casing resistance
27 differences and for errors in placements of the various
28 voltage measurement electrodes. The definitions provided in
29 Figures 1 through 6 are used to conveniently define many of
30 the symbols appearing in Figures 7 through 12.
31

32 From a technical drafting point of view, Figures 1, 2,
33 3, 4, and 5 in Serial No. 07/089,697 {Vail(542)} and in those
34 contained in this application are nearly identical. However,

1 the new drawings have been re-done using computer graphics
2 and the A-4 International Size. The following excerpt is
3 taken word-for-word from Serial No. 07/089,697:
4

5 "Fig. 1 shows a typical cased borehole found in an oil
6 field. The borehole 2 is surrounded with borehole casing 4
7 which in turn is held in place by cement 6 in the rock
8 formation 8. An oil bearing strata 10 exists adjacent to the
9 cased borehole. The borehole casing may or may not extend
10 electrically to the surface of the earth 12. A voltage
11 signal generator 14 (SG) provides an A.C. voltage via cable
12 16 to power amplifier 18 (PA). The signal generator
13 represents a generic voltage source which includes relatively
14 simple devices such as an oscillator to relatively complex
15 electronics such as an arbitrary waveform generator. The
16 power amplifier 18 is used to conduct A.C. current down
17 insulated electrical wire 20 to electrode A which is in
18 electrical contact with the casing. The current can return
19 to the power amplifier through cable 22 using two different
20 paths. If switch SW1 is connected to electrode B which is
21 electrically grounded to the surface of the earth, then
22 current is conducted primarily from the power amplifier
23 through cable 20 to electrode A and then through the casing
24 and cement layer and subsequently through the rock formation
25 back to electrode B and ultimately through cable 22 back
26 to the power amplifier. In this case, most of the current is
27 passed through the earth. Alternatively, if SW1 is connected
28 to insulated cable 24 which in turn is connected to electrode
29 F, which is in electrical contact with the casing, then
30 current is passed primarily from electrode A to electrode F
31 along the casing for a subsequent return to the power
32 amplifier through cable 22. In this case, little current
33 passes through the earth.
34

1 Electrodes C, D, and E are in electrical contact with
2 the interior of casing. In general, the current flowing
3 along the casing varies with position. For example, current
4 I_C is flowing downward along the casing at electrode C,
5 current I_D is flowing downward at electrode D, and current I_E
6 is flowing downward at electrode E. In general, therefore,
7 there is a voltage drop V_1 between electrodes C and D which
8 is amplified differentially with amplifier 26. And the
9 voltage difference between electrodes D and E, V_2 , is also
10 amplified with amplifier 28. With switches SW2 and SW3 in
11 their closed position as shown, the outputs of amplifiers 26
12 and 28 respectively are differentially subtracted with
13 amplifier 30. The voltage from amplifier 30 is sent to the
14 surface via cable 32 to a phase sensitive detector 34. The
15 phase sensitive detector obtains its reference signal from
16 the signal generator via cable 36. In addition, digital gain
17 controller 38 (GC) digitally controls the gain of amplifier
18 28 using cable 40 to send commands downhole. The gain
19 controller 38 also has the capability to switch the input
20 leads to amplifier 28 on command, thereby effectively
21 reversing the output polarity of the signal emerging from
22 amplifier 28 for certain types of measurements.

23
24 The total current conducted to electrode A is measured
25 by element 42. In the preferred embodiment shown in Fig. 1,
26 the A.C. current used is a symmetric sine wave and therefore
27 in the preferred embodiment, I is the 0-peak value of the
28 A.C. current conducted to electrode A. (The 0-peak value of
29 a sine wave is 1/2 the peak-to-peak value of the sine wave.)
30

31 In general, with SW1 connected to electrode B, current
32 is conducted through formation. For example, current ΔI is
33 conducted into formation along the length $2L$ between
34 electrodes C and E. However, if SW1 is connected to cable 24

1 and subsequently to electrode F, then no current is conducted
2 through formation to electrode B. In this case, $I_C = I_D = I_E$
3 since essentially little current ΔI is conducted into
4 formation.

5
6 It should be noted that if SW1 is connected to electrode
7 B then the current will tend to flow through the formation
8 and not along the borehole casing. Calculations show that
9 for 7 inch O.D. casing with a 1/2 inch wall thickness that if
10 the formation resistivity is 1 ohm-meter and the formation is
11 uniform, then approximately half of the current will have
12 flowed off the casing and into the formation along a length
13 of 320 meters of the casing. For a uniform formation with a
14 resistivity of 10 ohm-meters, this length is 1040 meters
15 instead." These lengths are respectively called
16 "Characteristic Lengths" appropriate for the average
17 resistivity of the formation and the type of casing used. A
18 Characteristic Length is related to the specific length of
19 casing necessary for conducting on approximately one-half the
20 initial current into a particular geological formation as
21 described below.

22
23 One embodiment of the invention described in Serial
24 No. 07/089,697 {Vail(542)} provides a preferred method of
25 operation for the above apparatus as follows: "The first
26 step in measuring the resistivity of the formation is to
27 "balance" the tool. SW1 is switched to connect to cable 24
28 and subsequently to electrode F. Then A.C. current is passed
29 from electrode A to electrode F thru the borehole casing.
30 Even though little current is conducted into formation, the
31 voltages V1 and V2 are in general different because of
32 thickness variations of the casing, inaccurate placements of
33 the electrodes, and numerous other factors. However, the
34 gain of amplifier 28 is adjusted using the gain controller so

1 that the differential voltage V3 is nulled to zero.
2 (Amplifier 28 may also have phase balancing electronics if
3 necessary to achieve null at any given frequency of
4 operation.) Therefore, if the electrodes are subsequently
5 left in the same place after balancing for null, spurious
6 effects such as thickness variations in the casing do not
7 affect the subsequent measurements.
8

9 With SW1 then connected to electrode B, the signal
10 generator drives the power amplifier which conducts current
11 to electrode A which is in electrical contact with the
12 interior of the borehole casing. A.C. currents from
13 1 amp o-peak to 30 amps o-peak at a frequency of typically 1
14 Hz are introduced on the casing here. The low frequency
15 operation is limited by electrochemical effects such as
16 polarization phenomena and the invention can probably be
17 operated down to .1 Hz and the resistivity still properly
18 measured. The high frequency operation is limited by skin
19 depth effects of the casing, and an upper frequency limit of
20 the invention is probably 20 Hz for resistivity measurements.
21 Current is subsequently conducted along the casing, both up
22 and down the casing from electrode A, and some current passes
23 through the brine saturated cement surrounding the casing and
24 ultimately through the various resistive zones surrounding
25 the casing. The current is then subsequently returned to the
26 earth's surface through electrode B."
27

28 Quoting further from Serial No. 07/089,697 {Vail(542)}:
29 "Fig. 2 shows the differential current conducted into
30 formation ΔI for different vertical positions z within a
31 steel cased borehole. z is defined as the position of
32 electrode D in Fig. 1. It should be noted that with a
33 voltage applied to electrode A and with SW1 connected to
34 electrode B that this situation consequently results in a

1 radially symmetric electric field being applied to the
2 formation which is approximately perpendicular to the casing.
3 The electrical field produces outward flowing currents such
4 as ΔI in Fig. 1 which are inversely proportional to the
5 resistivity of the formation. Therefore, one may expect
6 discontinuous changes in the current ΔI at the interface
7 between various resistive zones particularly at oil/water and
8 oil/gas boundaries. For example, curve (a) in Fig. 2 shows
9 the results from a uniform formation with resistivity ρ_1 .
10 Curve (b) shows departures from curve (a) when a formation of
11 resistivity ρ_2 and thickness T_2 is intersected where ρ_2 is
12 less than ρ_1 . And curve (c) shows the opposite situation
13 where a formation is intersected with resistivity ρ_3 which is
14 greater than ρ_1 which has a thickness of T_3 . It is obvious
15 that under these circumstances, ΔI_3 is less than ΔI_1 , which
16 is less than ΔI_2 .

17
18 Fig. 3 shows a detailed method to measure the parameter
19 V_o . Electrodes A, B, C, D, E, and F have been defined in
20 Fig. 1. All of the numbered elements 2 through 40 have
21 already been defined in Fig. 1. In Fig. 3, the thickness of
22 the casing is τ_1 , the thickness of the cement is τ_2 , and d is
23 the diameter of the casing. Switches SW1, SW2, and SW3 have
24 also been defined in Fig. 1. In addition, electrode G is
25 introduced in Fig. 3 which is the voltage measuring reference
26 electrode which is in electrical contact with the surface of
27 the earth. This electrode is used as a reference electrode
28 and conducts little current to avoid measurement errors
29 associated with current flow.

30
31 In addition, SW4 is introduced in Fig. 3 which allows
32 the connection of cable 24 to one of the three positions:
33 to an open circuit; to electrode G; or to the top of the
34 borehole casing. And in addition in Fig. 3, switches SW5,

1 SW6, and SW7 have been added which can be operated in the
2 positions shown. (The apparatus in Fig. 3 can be operated in
3 an identical manner as that shown in Fig. 1 provided that
4 switches SW2, SW5, SW6, and SW7 are switched into the
5 opposite states as shown in Fig. 3 and provided that SW4
6 is placed in the open circuit position.)
7

8 With switches SW2, SW5, SW6, and SW7 operated as shown
9 in Fig. 3, then the quantity V_o may be measured. For a given
10 current I conducted to electrode A, then the casing at that
11 point is elevated in potential with respect to the zero
12 potential at a hypothetical point which is an "infinite"
13 distance from the casing. Over the interval of the casing
14 between electrodes C, D, and E in Fig. 3, there exists an
15 average potential over that interval with respect to an
16 infinitely distant reference point. However, the potential
17 measured between only electrode E and electrode G
18 approximates V_o provided the separation of electrodes A, C,
19 D, and E are less than some critical distance such as 10
20 meters and provided that electrode G is at a distance
21 exceeding another critical distance from the casing such as
22 10 meters from the borehole casing. The output of amplifier
23 28 is determined by the voltage difference between electrode
24 E and the other input to the amplifier which is provided by
25 cable 24. With SW1 connected to electrode B, and SW4
26 connected to electrode G, cable 24 is essentially at the same
27 potential as electrode G and V_o is measured appropriately
28 with the phase sensitive detector 34. In many cases, SW4 may
29 instead be connected to the top of the casing which will work
30 provided electrode A is beyond a critical depth ...".
31

32 Quoting further from Serial No. 07/089,697 {Vail(542)}:
33 "For the purposes of precise written descriptions of the
34 invention, electrode A is the upper current conducting

1 electrode which is in electrical contact with the interior of
2 the borehole casing; electrode B is the current conducting
3 electrode which is in electrical contact with the surface of
4 the earth; electrodes C, D, and E are voltage measuring
5 electrodes which are in electrical contact with the interior
6 of the borehole casing; electrode F is the lower current
7 conducting electrode which is in electrical contact with the
8 interior of the borehole casing; and electrode G is the
9 voltage measuring reference electrode which is in electrical
10 contact with the surface of the earth.

11
12 Furthermore, V_0 is called the local casing potential.
13 An example of an electronics difference means is the
14 combination of amplifiers 26, 28, and 30. The differential
15 current conducted into the formation to be measured is ΔI .
16 The differential voltage is that voltage in Figure 1 which is
17 the output of amplifier 30 with SW1 connected to electrode B
18 and with all the other switches in the positions shown.

19
20 Further quoting from Serial No. 07/089,697 {Vail(542)}:
21 "Fig. 4 is nearly identical to Fig. 1 except the electrodes C
22 and D are separated by length L_1 , electrodes D and E are
23 separated by L_2 , electrodes A and C are separated by L_3 and
24 electrodes E and F are separated by the distance L_4 . In
25 addition, r_1 is the radial distance of separation of
26 electrode B from the casing. And Z is the depth from the
27 surface of the earth to electrode D. Fig. 5 is nearly
28 identical to Fig. 3 except here too the distances L_1 , L_2 , L_3 ,
29 L_4 , r_1 , and Z are explicitly shown. In addition, r_2 is also
30 defined which is the radial distance from the casing to
31 electrode G. As will be shown explicitly in later analysis,
32 the invention will work well if L_1 and L_2 are not equal. And
33 for many types of measurements, the distances L_3 and L_4 are
34

1 not very important provided that they are not much larger in
2 magnitude than L_1 and L_2 ."

3
4 Figure 6 was first described in Serial No. 07/434,886
5 {Vail(626)} which states: "For the purpose of logical
6 introduction, the elements in FIG. 6 are first briefly
7 compared to those in FIGS. 1-5. Elements No. 2, 4, 6, 8,
8 and 10 have already been defined. Electrodes A, B, C, D, E,
9 F, G and the distances L_1 , L_2 , L_3 , and L_4 have already been
10 described. The quantities δi_1 and δi_2 have already been
11 defined in the above text. Amplifiers labeled with legends
12 A1, A2, and A3 are analogous respectively to amplifiers 26,
13 28, and 30 defined in FIGS. 1, 3, 4, and 5. In addition, the
14 apparatus in Fig. 6 provides for the following:

15 (a) two signal generators labeled with legends "SG 1 at
16 Freq F(1)" and "SG 2 at Freq F(2)";

17 (b) two power amplifiers labeled with legends "PA 1"
18 and "PA 2";

19 (c) a total of 5 phase sensitive detectors defined as
20 "PSD 1", "PSD 2", "PSD 3", "PSD 4", and "PSD 5", which
21 respectively have inputs for measurement labeled as "SIG",
22 which have inputs for reference signals labeled as "REF",
23 which have outputs defined by lines having arrows pointing
24 away from the respective units, and which are capable of
25 rejecting all signal voltages at frequencies which are not
26 equal to that provided by the respective reference signals;

27 (d) an "Error Difference Amp" so labeled with this
28 legend in FIG. 6;

29 (e) an instrument which controls gain with voltage,
30 typically called a "voltage controlled gain", which is
31 labeled with legend "VCG";

32 (f) an additional current conducting electrode labeled
33 with legend "H" (which is a distance L_5 - not shown - above
34 electrode A);

1 (g) an additional voltage measuring electrode labeled
2 with legend J (which is a distance L_6 - not shown - below
3 electrode F);

4 (h) current measurement devices, or meters, labeled
5 with legends "I1" and "I2";

6 (i) and differential voltage amplifier labeled with
7 legend "A4" in Fig. 6."
8

9 Serial No. 07/434,886 {Vail(626)} further describes
10 various cables labeled with legends respectively 44, 46, 48,
11 50, 52, 54, 56, 58, 60, 62, and 64 whose functions are
12 evident from Figure 6.
13

14 Serial No. 07/434,886 {Vail(626)} further states: "The
15 outputs of PSD 1, 2, 3, and 4 are recorded on a digital
16 recording system 70 labeled with legend "DIG REC SYS". The
17 respective outputs of the phase sensitive detectors are
18 connected to the respective inputs of the digital recording
19 system in FIG. 6 according to the legends labeled with
20 numbers 72, 74, 76, 78, and 80. One such connection is
21 expressly shown in the case of element no. 72."
22

23 Serial No. 07/434,886 {Vail(626)} teaches in great
24 detail that it is necessary to accurately measure directly,
25 or indirectly, the resistance between electrodes C-D (herein
26 defined as "R1") and the resistance between electrodes D-E
27 (herein defined as "R2") in Figures 1, 3, 4, 5 and 6 to
28 precisely measure current leakage into formation and
29 formation resistivity from within the cased well. Please
30 refer to Equations 1-33 in Serial No. 07/434,886 {Vail(626)}
31 for a thorough explanation of this fact. The parent
32 application, Serial No. 06/927,115 {Vail(989)} and
33 the following Continuation-in-Part Application Serial
34 No. 07/089,697 {Vail(542)} taught that measurement of the

1 resistance of the casing between voltage measurement
2 electrodes that engage the interior of the casing are very
3 important to measure formation resistivity from within the
4 casing.

5
6 Using various different experimental techniques that
7 result in current flow along the casing between current
8 conducting electrodes A and F in Figures 1, 3, 4, 5, and 6
9 result in obtaining first compensation information related to
10 a first casing resistance defined between voltage measurement
11 electrodes C and D. Similarly, using various different
12 experimental techniques that result in current flow along the
13 casing between current conducting electrodes A and F in
14 Figures 1, 3, 4, 5, and 6 result in obtaining second
15 compensation information related to a second casing
16 resistance between voltage measurement electrodes D and E.
17 Figures 1, 3, 4, 5, and 6 all provide additional means to
18 cause current to flow into formation, and the measurements
19 performed while current is flowing into the formation is
20 called the measurement information related to current flow
21 into formation. Such measurement information is used to
22 determine a magnitude relating to formation resistivity.
23 Figures 7 -12 in the remaining application also provide
24 various means to provide measurement information, and
25 respectively first and second compensation information, along
26 with additional information in several cases.

27
28 Figure 7 is closely related to Figure 6. However, in
29 Figure 7, amplifier A3 that is shown in Figure 6, which can
30 be either downhole, or uphole, has been removed. Further,
31 the Error Difference Amp, cable 60, and the VCG have also
32 been removed. In Figure 7, the output of amplifier A1 at
33 frequency F(1) is measured by PSD 4 and the output of
34 amplifier A1 at frequency F(2) is measured by PSD 2 - as was

1 the case in Figure 6. However, in Figure 7, the output of
2 amplifier A2 at F(1) is measured by PSD 1 and the output of
3 amplifier A2 at F(2) is measured by PSD 3. In Figure 7,
4 current at the frequency of F(1) is conducted into formation
5 resulting in measurement information being obtained from PSD
6 1 and PSD 4. Current at the frequency of F(2) is caused to
7 flow along the casing between electrodes H and F to provide
8 compensation for casing thickness variations and to provide
9 compensation for errors in the placement of the voltage
10 measurement electrodes. First compensation information
11 related to the casing resistance between electrodes C and D
12 is obtained from PSD 2. Second compensation information
13 related to the casing resistance between electrodes D and E
14 is obtained from PSD 3. Analogous algebra exists for the
15 operation of the apparatus in Figure 7 to Equations 1-33 in
16 Serial No. 07/434,886 {Vail(626)} that provides compensation
17 for casing resistance differences and for errors of
18 placements of the three spaced apart voltage measurement
19 electrodes C, D, and E.

20
21 Figure 8 is similar to Figure 7 except that electrode D
22 in Figure 7 has been intentionally divided into two separate
23 electrodes D1 and D2. D1 and D2 do not overlap and are
24 separated by a distance L9. Electrodes C and D1 are
25 separated by distance L1*. Electrodes D2 and E are separated
26 by the distance L2*. If D(1) and D(2) overlap, then the
27 invention has the usual configuration described in Figures 1,
28 3, 4, 5, 6, and 7. Then consider the situation wherein
29 electrodes D(1) and D(2) do not overlap. Suppose they are
30 separated by 1 inch. Then suppose that the separation
31 distance between C to D(1) is 20 inches and suppose that the
32 separation distance between D(2) to E is also 20 inches.
33 Then clearly, the invention will still work, although there
34 will be some error in the current leakage measurement caused

1 by the lack of measurement information from the 1 inch
2 segment. Perhaps the error shall be on the order of 1 inch
3 divided by 20 inches, or on the order of an approximate 5%
4 error. Figure 8 shows an apparatus having four spaced apart
5 voltage measurement electrodes that compensates for casing
6 thickness variations and for errors in placements of
7 electrodes by providing measurements of the casing resistance
8 R1 between electrodes C and D1 at the frequency of F(2)
9 by PSD 2 and by providing measurements of the casing
10 resistance R2 between electrodes D2 and E at the frequency
11 F(2) by PSD 3.

12
13 Figure 8 may be operated in a particularly simple
14 manner. The signal between electrodes C - D1 can be used to
15 control current flowing along the casing at the frequency
16 F(1) (by using electronics, not shown, of the type used to
17 control currents in Figure 6). Then the signal between
18 electrodes D2 - E can be used to measure information related
19 to current flow along the casing and into the formation at
20 the frequency of F(1). Despite the fact that electrodes C-
21 D1 are used to "control current", nonetheless, the apparatus
22 so described requires at least 3 spaced apart voltage
23 measurement electrodes and is therefore another embodiment of
24 the invention herein.

25
26 Figure 9 shows certain changes to the apparatus defined
27 in Figure 8. Changes from Figure 8 includes cables 88 and 90
28 that are meant to convey signals to the appropriate phase
29 sensitive detectors shown in Figure 8 for the purposes of
30 simplicity; extra variable resistor labeled with legend "VR1"
31 placed in series with current meter labeled with legend "I1"
32 connected to cable 92 that provides current at the frequency
33 of F(1) to the upper current conducting electrode here
34 defined as A1; extra variable resistor labeled with legend

1 "VR2" placed in series with another current meter labeled
2 with legend "I3" connected to cable 94 that provides current
3 at the frequency of F(1) to new electrode A2. Electrodes H
4 and F are shown connected to cables 98 and 100 respectively
5 which operate as shown in Figure 8, but many of the details
6 are omitted in Figure 9 in the interest of simplicity. In
7 Figure 9, current at the frequency of F(2) is passed between
8 electrodes H and F as in Figure 8 which provides first
9 compensation information related to current flow through the
10 casing resistance ("R1") between electrodes C-D1 and second
11 compensation information related to current flow through the
12 casing resistance ("R2") between electrodes D2-E, although
13 many of the details are not shown in Figure 9 for the
14 purposes of simplicity. The purpose of electrodes A1 and A2
15 in Figure 9 are to provide simultaneously upward and downward
16 flowing currents along the casing at the frequency of F(1).
17 Such simultaneously upward and downward flowing currents
18 along the casing are hereinafter defined as "counter-flowing
19 currents". Such counter-flowing currents in the vicinity of
20 the voltage measurement electrodes C, D1, D2, and E minimize
21 the "common mode signal" input to the amplifiers A1 and A2.
22 Therefore, the signal output of amplifiers A1 and A2 in the
23 presence of such counter-flowing currents tends to be more
24 responsive to the current actually flowing into formation and
25 less responsive to the relatively larger currents flowing
26 along the casing. Other apparatus showing methods of
27 introducing counter-flowing currents on the casing include
28 Figures 22 and 23 of Serial No. 07/089,697 {Vail(542)}. The
29 current actually flowing into the formation at the frequency
30 of F(1) generates voltages across amplifiers A1 and A2
31 responsive to the current flow into formation that results in
32 measurement information at the frequency of F(1) from phase
33 sensitive detectors as shown in Figure 8. That measurement
34 information is used to determine a magnitude relating to

1 formation resistivity, including information related to the
2 resistivity of the adjacent geological formation.

3
4 Figure 10 improves the measurement accuracy of the
5 apparatus defined in Figure 9. Figure 10 is similar to
6 Figure 9 except that in Figure 10 extra voltage measurements
7 P, Q, R, and S have been added. The purpose of additional
8 voltage measurement electrodes P and Q are to sense the
9 current flowing along the casing at the frequency of F(1)
10 between P and Q. Further electronics, not shown, are used to
11 control the variable resistor VR1 such that the current
12 flowing along the casing remains relatively constant at the
13 frequency of F(1). Please recall that electrodes H and F are
14 used to conduct current along the casing at the frequency of
15 F(2) and therefore, measurements of the potential difference
16 between P and Q can be used to measure the casing resistance
17 between P and Q that is called "R3" which is therefore used
18 as necessary information to keep the current flowing at the
19 frequency F(1) through R3. Figure 6 has already provided
20 means to maintain equality of currents flowing along the
21 casing, and similar apparatus can be adapted herein to
22 maintain the equality of current flow at the frequency of
23 F(1) between P and Q. Similarly comments can be made
24 regarding new electrodes R and S which can be used to keep
25 the current flowing along the casing at the frequency of F(1)
26 constant through the casing resistance between electrodes R
27 and S, that is "R4" by controlling the variable resistor VR2.
28 If the current flowing through R3 at F(1) is held constant as
29 the device vertically logs the well, then that shall serve to
30 minimize the influence of the lack of information caused by
31 the separation of electrodes D1 and D2. Similarly, if the
32 current flowing through R4 at F(1) is held constant, that too
33 serves to minimize the influence of the lack of information
34 caused by the separation between electrodes D1 and D2.

1 Consequently, extra current control means have been provided
2 to control the current flow along the casing at the F(1) to
3 minimize the influence of the lack of information from
4 portions of the casing having no voltage measurement
5 electrodes present. With suitably added amplifiers, these
6 new electrode pairs can be used to independently monitor the
7 counter-flowing currents at the measurement frequency at the
8 positions shown. In particular, electrode pairs P-Q and R-S
9 can be provided with amplifiers and feedback circuitry that
10 drives the currents to A1 and A2 such that the counter-
11 flowing current at the measurement frequency (for example, 1
12 Hz) is driven near zero across the voltage measurement
13 electrodes C-D1 and D2-E. Regardless of the details of
14 operation chosen however, the invention disclosed in Figure
15 10 provides four spaced electrodes means that provides
16 measurement information related to current flow into
17 formation, and respectively, first and second compensation
18 information related to measurements of R1 and R2 between
19 respectively electrodes C-D, and D-E that are used to
20 determine a magnitude related to formation resistivity.
21 Altogether, Figure 10 shows a total of 8 each voltage
22 measurement electrodes operated as 4 pairs of voltage
23 measurement electrodes.

24
25 Figure 11 is similar to Figure 10 except that electrodes
26 D1 and D2 have been re-combined back into one single
27 electrode D herein. However, the extra potential voltage
28 measurement electrodes P-Q, and R-S remain in Figure 11 to
29 maintain equality of the magnitude of the counter-flowing
30 currents along the casing at the frequency of F(1).
31 Maintaining the equality of counter-flowing currents along
32 the casing at F(1), and ideally causing the counter-flowing
33 currents to approach the limit of zero net current flowing up
34 or down the casing at the frequency of F(1) will result in

1 improved measurement accuracy. Regardless of the details of
2 operation chosen however, the invention disclosed in Figure
3 11 provides a minimum of 3 spaced electrodes means that
4 provides measurement information related to current flow into
5 formation, and respectively, first and second compensation
6 information related to measurements of R1 and R2 between
7 respectively electrodes C-D, and D-E that are used to
8 determine a magnitude related to formation resistivity.
9 Altogether, Figure 11 shows a total of 7 each voltage
10 measurement electrodes operated as 4 pairs of voltage
11 measurement electrodes.

12
13 Figure 12 is similar to Figure 11 except that the extra
14 potential voltage measurement electrodes P-Q and
15 R-S have been removed. It should be noted that the apparatus
16 defined in Figure 12 results in knowledge of the measurement
17 current leaking into formation, knowledge of the resistance
18 R1 between voltage measurement electrodes C-D, and the
19 knowledge of the resistance R2 between voltage measurement
20 electrodes D-E. Therefore, the apparatus in Figure 12
21 provides knowledge of the net current at F(1) flowing through
22 resistor R1 between electrodes C-D. Similarly, the apparatus
23 in Figure 12 provides knowledge of the net current at F(1)
24 flowing through resistor R2 between electrodes D-E. Extra
25 control circuitry, not shown, can be adapted as in Figure 6
26 to minimize the net counter-flowing currents flowing by the
27 combined resistors R1 and R2 to improve measurement accuracy.
28 Regardless of the details of operation chosen however, the
29 invention disclosed in Figure 12 provides a minimum of 3
30 spaced apart electrode means that provide measurement
31 information related to current flow into formation, and
32 respectively, first and second compensation information
33 related to measurements of R1 and R2 between respectively
34

1 electrodes C-D, and D-E that are used to determine a
2 magnitude related to formation resistivity.

3
4 The apparatus in Figure 12 may be operated in a
5 particularly simple manner. Information from pair C-D can be
6 used to control the magnitude of the current flowing along
7 the casing at the frequency of F(1), and keep it constant.
8 Then information from pair D-E can be used to infer
9 geophysical parameters from measurements of the current at
10 the frequency of F(1). Despite the fact that the first pair
11 C-D is used primarily herein "to control current", the
12 apparatus so described nonetheless requires 3 spaced apart
13 voltage measurement electrodes which engage the interior of
14 the casing and is therefore simply another embodiment of the
15 invention herein.

16
17 Figure 13 is functionally identical to Figure 26 from
18 Serial No. 07/089,697 that is U.S. Patent No. 4,882,542,
19 showing an apparatus having multiple voltage measurement
20 electrodes engaging the interior of the casing that is marked
21 with the legend "Prior Art". Individual potential voltage
22 measurement electrodes k, l, m, n, o, p, q, r, s, and t
23 electrically engage the casing. In principle, any total
24 number Z of such potential voltage measuring electrodes can
25 be made to electrically engage the interior of the casing.
26 During the calibration step described in Vail(542), current
27 is passed along the casing resulting in the knowledge of the
28 respective casing resistances between each potential voltage
29 measurement electrode. The casing resistance between
30 electrodes k and l is defined herein as $R(k,l)$. The casing
31 resistance between electrodes l and m is defined herein as
32 $R(l,m)$. The casing resistance between m and n is defined
33 herein $R(m,n)$. The casing resistance between n and o is
34 defined herein as $R(n,o)$. By analogy, the casing resistances

1 R(o,p), R(p,q), R(q,r), R(r,s) and R(s,t) are defined herein.
2 In principle, any number of casing resistances can be defined
3 for any number Z of electrodes which electrically engage the
4 interior of the casing. The distance along the casing
5 between electrodes k and l is defined herein as L(k,l). The
6 distance along the casing between electrodes l and m is
7 defined herein as L(l,m). The distance along the casing
8 between electrodes m and n is defined herein as L(m,n). The
9 distance along the casing between electrodes n and o is
10 defined herein as L(n,o). By analogy, the distances of
11 separation of appropriate electrodes are defined herein as
12 L(o,p), L(p,q), L(q,r), L(r,s,) and L(s,t). In principle,
13 any number of distances can be defined between any number Z
14 electrodes which electrically engage the interior of the
15 casing. The distance of separation between electrodes can be
16 chosen to be any distance. They may be chosen to be equal or
17 they can be chosen not to be equal, depending upon chosen
18 function. For example, L(k,l) can be chosen to be 3 inches.
19 L(l,m) can be chosen to be 6 inches. L(m,n) can be chosen to
20 be 12 inches. L(n,o) can be chosen to be 20 inches. L(o,p)
21 can be chosen to be 52 inches. L(p,q) can be chosen to be 60
22 inches. L(q,r) can be chosen to be 120 inches. Further,
23 electrodes s and t can be disconnected. Such an array can
24 measure the potential voltage distribution along the casing
25 or the potential voltage profile along the casing in response
26 to calibration currents primarily flowing along the casing
27 and in response to the measurement currents flowing along the
28 casing and into the formation. The calibration current can
29 be at chosen to be the same frequency as the measurement
30 current as originally described in Vail(989) or can be at a
31 different frequency as described in Vail(626). The above
32 described variable spacing can be used to infer the vertical
33 and radial variations of the geological formation, the
34 vertical distribution of geological beds, and other

1 geological information. Regardless of the details of
2 operation chosen however, the invention disclosed in Figure
3 13 provides a minimum of 3 spaced apart voltage measurement
4 electrode means that provide measurement information related
5 to current flow into formation, and respectively, first and
6 second compensation information related to measurements of at
7 least two casing resistances respectively between the three
8 voltage measurement electrodes, wherein said measurement
9 information and the first and second compensation information
10 are used to determine a magnitude related to formation
11 resistivity. Figure 12 and the text herein further shows
12 that a plurality of spaced apart electrodes along the casing,
13 which may be chosen to be spaced at various different
14 intervals, provide multiple measurements of quantities
15 related to current flow into formation, and provide multiple
16 measurements of the resistances of the casing spanned by the
17 particular number of chosen spaced apart electrodes that may
18 be used to infer geophysical information including the
19 resistivity of the adjacent formation.
20

21 It should also be noted that Serial No. 07/089,697
22 {Vail(542)} describes many different means to measure voltage
23 profiles on the casing including those shown in Figures 25,
24 26, 27, 28, and 29 therein. Those drawings describe several
25 other apparatus geometries having multiple electrodes.
26

27 It may also be worthwhile to note here that several of
28 the figures show different preferred embodiments of the
29 invention. In Figures 1, 2, 3, 4, and 5, switch 22 is in
30 one of several positions, so this switch "alters" between one
31 state and another one, and hence such methods of measurement
32 are sometimes referred to as an "alter method of
33 measurement". Figures 6, 7 and 8 explicitly shows two
34 frequencies of operation at the same time, and hence, such

1 methods of measurement are sometimes referred to as a
2 "two frequency method of measurement". In Figures 6, 7, and
3 8, F(2) may be any frequency, and F(1) may be any frequency -
4 provided the other above requirements for the measurement are
5 otherwise satisfied. It is also evident from the above
6 description that more than two frequencies may be used, and
7 hence such methods of measurement are sometimes referred to
8 as a "multiple frequency of method of measurement". And
9 lastly, it is possible to perform measurements of resistivity
10 using hybrid methods, wherein certain measurements are
11 performed at one stage of an "alter method of measurement",
12 and yet other measurements are performed using a "two
13 frequency method of measurement" and/or a "multiple frequency
14 method of measurement". There are many variations of the
15 preferred embodiments of the invention.

16
17 Therefore, measurements of the current leakage may be
18 performed using an "alter method of measurement", a "two
19 frequency method of measurement" or a "multiple frequency
20 method of measurement".

21
22 Therefore, measurements of the potential voltage may be
23 performed using an "alter method of measurement", a "two
24 frequency method of measurement" or a "multiple frequency
25 method of measurement".

26
27 Various embodiments of the invention herein provide many
28 different manners to introduce current onto the casing, a
29 portion of which is subsequently conducted through formation.
30 Various embodiments herein provide many different methods to
31 measure voltage levels at a plurality of many points on the
32 casing to provide a potential voltage profile along the
33 casing which may be interpreted to measure the current
34 leaking off the exterior of the casing from within a finite

vertical section of the casing. Regardless of the details of operation chosen however, the invention herein disclosed provides a minimum of 3 spaced apart voltage measurement electrode means that provides measurement information related to current flow into the geological formation, and respectively, first and second compensation information related to measurements of at least two separate casing resistances between the three spaced apart voltage measurement electrodes, wherein the measurement information and the first and second compensation information are used to determine a magnitude related to formation resistivity.

Figure 14 is an exact copy of Figure 24 from U.S. Patent No. 4,882,542 {Vail(542)}, that issued on 11/21/1989, that is Serial No. 07/089,697, that has the filing date of 8/26/1987. Here, the number of the figure has been changed from "Fig. 24" to "Fig. 14". All the numerals through numeral 42 have already been defined herein. The following excerpt is quoted from Serial No. 07/089,697 {Vail(542)} commencing on page 20, line 3, and ending on page 20, line 61, as follows (except that the phrase "Fig. 24" has been replaced by the phrase "Fig. 14"):

"Fig. 14 shows another embodiment of the invention. The purpose of Fig. 14 is to present various alternatives for the placement of electrode B and to further discuss requirements which electrode B must satisfy for proper operation of various embodiments of the invention. Here, most all of the elements have been defined in Fig. 1 except here SW1C replaces SW1 in Fig. 1. Switch SW1C may be used to connect to alternative grounding positions shown figuratively as B, B₁, B₂, and B₃ in Fig. 14. Electrode B has already been described. B₁ is an electrode in electrical contact with the

1 interior of the casing which is located beyond a
2 critical distance, L_c , away from electrode A.
3 As long as the length of casing between A and B_1 , L_8 , is
4 comparable to or larger than L_c , then the electric field
5 is primarily perpendicular to the casing when electrode
6 A is energized, and the invention works in the usual
7 fashion. The critical distance L_c is that length of
8 casing adjacent to a formation where the series
9 resistance to current flow equals the contact resistance
10 of the pipe adjacent to the formation. (For a uniform
11 formation, that distance can be calculated by requiring
12 that at a particular length L_c , the series resistance to
13 current flow along the length L_c of the casing which is
14 given by the algebraic expression ($L_c r$), where r is
15 defined in Eq. 1, is equal to the resistance R_c in Eq. 6
16 for the particular length $L_c / 2$. This equation is then
17 solved for the length L_c . This is also the approximate
18 distance where half of the current flows off the casing
19 into the formation which has already been discussed).
20 The requirement on the length of L_8 is a matter of
21 convenience only, because for shorter lengths of L_8 , as
22 long as the placement of electrode B_1 is such that it
23 allows the generation of any significant component of
24 the electric field perpendicular to the casing in the
25 vicinity of electrode A, then current is conducted into
26 formation from the casing adjacent to electrode A, and
27 the invention functions properly. In addition, B_2 is an
28 electrode in electrical contact with the top of the
29 borehole casing. Here too, as long as the resistance of
30 the length of casing between A and B_2 is comparable to
31 or larger than the total resistance to current flow
32 between electrode A and electrode B, then the electric
33 field is primarily perpendicular to the casing when
34 electrode A is energized, and the invention works in the

1 usual fashion. And finally, B_3 is another earth ground,
2 and it's position is immaterial provided that the
3 electric field produced on the exterior of the casing is
4 primarily perpendicular to the casing which will allow
5 proper measurement of the resistivity of the geological
6 formation. Although the electric field is primarily
7 perpendicular to the casing at great depths independent
8 of the position of the ground return (B , B_1 , B_2 , or B_3),
9 there none-the-less should be small detectable
10 differences related to the different current paths.
11 Therefore, different grounding returns could provide a
12 means of measuring the resistivity of different selected
13 portions of the formation such as the resistivity of
14 different quadrants. Such measurements are only a minor
15 modification of the invention."
16

17 As stated earlier, all the elements through element 42
18 in Figure 14 have already been defined. The remaining
19 legends in Figure 14 are listed as follows: L_7 , that is the
20 distance below the surface to the earth to electrode B_1 ;
21 L_8 , that is the distance between electrode B_1 and
22 electrode A; r_1 , that is the radial distance from the cased
23 well to electrode B; and r_3 that is the radial position from
24 the well to electrode B_3 .
25

26 It should be noted that above described calculation for
27 L_c is explicitly presented in Equation 1 on page 9 of U.S.
28 Patent No. 5,187,440 {Vail(440)} that issued on 2/16/1993,
29 that is Serial No. 07/749,136, and that has the Filing Date
30 of 8/23/91, an entire copy of which is included herein by
31 reference.
32

33 It is useful to further discuss certain the above quote
34 related to Figure 14. One sentence reads: "The requirement

1 on the length of L_g is a matter of convenience only, because
2 for shorter lengths of L_g , as long as the placement of
3 electrode B_1 is such that it allows the generation of any
4 significant component of the electric field perpendicular to
5 the casing in the vicinity of electrode A, then current is
6 conducted into formation from the casing adjacent to
7 electrode A, and the invention functions properly." The
8 critical operational term here is "...generation of any
9 significant component of the electric field...".
10

11 Another sentence in that long quote related to Figure 14
12 reads as follows: "Although the electric field is primarily
13 perpendicular to the casing at great depths independent of
14 the position of the ground return (B , B_1 , B_2 , or B_3), there
15 none-the-less should be small detectable differences related
16 to the different current paths. Therefore, different
17 grounding returns could provide a means of measuring the
18 resistivity of different selected portions of the formation
19 such as the resistivity of different quadrants. Such
20 measurements are only a minor modification of the invention."
21

22 One "...minor modification of the invention..." quoted
23 above, relates to the above observation that many different
24 positions electrode B_1 result in the "...the generation of
25 any significant component of the electric field perpendicular
26 to the casing in the vicinity of electrode A...". Further,
27 the "...different grounding returns could provide a means of
28 measuring the resistivity of different selected portions of
29 the formation..." From this description, it is evident that
30 another preferred embodiment of the invention provides a
31 means of adjusting the magnitude of the electric field
32 perpendicular to the casing applied to any one geological
33 formation at chosen depth z in Fig. 14 by performing
34 measurements with electrode B_1 placed at a first distance

1 L_8 (a) above electrode A; and then by performing measurements
2 with electrode B_1 placed a second distance L_8 (b) above
3 electrode A; and then by performing measurements perhaps
4 another time by performing measurements at a third distance
5 L_8 (c) above electrode A. In principle, any number of such
6 measurements could be made.

7
8 Furthermore, there is no particular necessary reason in
9 a deep well, with sufficient casing below electrode F, that
10 electrode B_1 must be located above electrode A. In fact,
11 with a sufficiently deep well, electrode B_1 may be located at
12 any chosen distance below electrode F. In this preferred
13 embodiment, electrode $B_1(L_8)$ may be placed at any distance L_8
14 above electrode A. Here, the position of electrode B_1 is a
15 function of L_8 . Similarly, any such electrode that is
16 located below electrode F would be separated by a distance L_9
17 below electrode F. This electrode will be defined herein to
18 be $B_1^*(L_9)$, where the quantity B_1^* indicates that electrode
19 is located below electrode F in Figure 14, and is at a
20 distance L_9 below electrode F in Figure 14. However, these
21 legends have not been added to Figure 14 for the sake of
22 simplicity. Further, the current return electrode B_1 above
23 electrode A, and any current return electrode B_1^* located
24 below electrode F in Figure 14 may be energized
25 simultaneously using apparatus and methods already described
26 above. This in turn provides "...means of measuring the
27 resistivity of different selected portions of the
28 formation...". In particular, if the strength of the
29 electric field perpendicular to the casing is adjusted from a
30 first value of the electric field to a second value of the
31 electric field, wherein said second value is greater than the
32 first value, then it is evident that the "radius of
33 investigation" of the formation has been increased. In
34 general, for any particular value of the electric field

1 perpendicular to the casing, there is an appropriate "radius
2 of investigation" for that magnitude of electric field.
3 Performing measurements for various different positions of
4 one, or more current return electrodes, provides a method for
5 measuring the resistivity of the geological formation for
6 different radii of investigation. Therefore, adjusting the
7 various different current return electrodes in the casing
8 provides methods of operation to vary the "radius of
9 investigation", a term defined herein.

10
11 The preferred embodiments described above in relation to
12 Figure 14 provides a means of adjusting the magnitude of the
13 electric field perpendicular to the casing applied to any one
14 geological formation at any depth z in Fig. 14 by performing
15 measurements with different placements of one or more of the
16 current return electrodes. For any such magnitude of applied
17 electric field, then plots similar to those shown in Figure 2
18 will be obtained. However, for larger applied fields, the
19 maximum value of ΔI will be correspondingly larger. Put
20 another way, for a first value of the applied electric field,
21 then a first value of $\Delta I(\text{first})$ will be observed. For a
22 larger second value of the applied electric field, then a
23 second value of $\Delta I(\text{second})$ will be observed. In the example
24 cited, $\Delta I(\text{second})$ will be larger than $\Delta I(\text{first})$.
25 Such procedures amount to adjusting the radius of
26 investigation, or the "50% radius of investigation",
27 a term used in the above defined literature.

28
29 In Vail(440), Figure 6 therein shows yet another
30 grounding position, or one more position for another current
31 return electrode that is labeled with the legend B_4 therein.
32 The point is that the inventor has provided many possible
33 positions for one or more current return electrodes
34 generically identified by the symbol "B" in many of the

1 figures related to the Vail Patents in this field. For
2 many preferred embodiments, the term "grounding position",
3 "current return electrode", "ground return electrode",
4 "ground return electrode in the cased well", "current return
5 electrode to generate an electric field in the formation
6 exterior to the casing", and similar variations, may all be
7 used equivalently for the purposes herein.

8
9 In addition, Figure 48 in U.S. Patent No. 4,882,542
10 Vail (542) shows at least two apparatus disposed within a
11 drill pipe, each having their own current introducing
12 electrodes.

13
14 Yet further, Figures 6-12 herein each have multiple
15 sets of current introducing electrodes disposed within the
16 wellbore.

17
18 Therefore, the invention has described many different
19 preferred embodiments of apparatus and methods of operation
20 that provide for two or more current conducting electrodes in
21 electrical contact with the interior of the casing to measure
22 formation resistivity. The invention has further described
23 many different preferred embodiments of the apparatus and
24 methods of operation that provide for at least two current
25 conducting electrodes in electrical contact with the interior
26 of the casing and one in contact with the top of the casing
27 to measure formation resistivity.

28
29 Accordingly, the invention has provide apparatus and
30 methods of operation to determine the resistivity of a
31 formation adjacent to a borehole having casing with an
32 apparatus having all the current conducting electrodes
33 within the cased well. Figure 14 shows such an apparatus
34 when element 22 is connected through SW1C to electrode B₁.

1 Therefore, and with reference to Figure 14 and other
2 related figures herein, one embodiment of the invention is an
3 apparatus to provide information useful to determine the
4 resistivity of a geological formation from within a cased
5 well that has a first electrode that electrically engages a
6 first particular section of casing at a specific depth within
7 the well for receiving first signals having voltage related
8 information; a second electrode that electrically engages the
9 first particular section of casing for receiving second
10 signals having voltage related information located a first
11 distance above said first electrode wherein the magnitude of
12 the resistance of the portion of casing between said first
13 and second electrodes is the first resistance; and a third
14 electrode that electrically engages the first particular
15 section of casing for receiving third signals having voltage
16 related information located a second distance below said
17 first electrode wherein the magnitude of the resistance of
18 the portion of casing between said first and third electrodes
19 is the second resistance. This embodiment also has a fourth
20 electrode that electrically engages the casing at a point
21 located a third distance above said second electrode and
22 a fifth electrode that electrically engages the casing at a
23 point located a fourth distance above said fourth electrode.
24 This embodiment also provides means to conduct a first
25 current from said fourth electrode to said fifth electrode.
26 Further, said fourth distance is chosen such that at least a
27 portion of said first current flows into the formation of
28 interest. Figure 14 shows an apparatus having means to
29 measure said first resistance and said second resistance.
30 Figure 14 also shows means for processing said first, second
31 and third signals from said first, second, and third
32 electrode means thereby providing information useful to
33 determine the resistivity of the formation of interest.
34

1 With reference to Figure 14 and to other related figures
2 and disclosure, another embodiment provides information
3 useful to determine the resistivity of a geological formation
4 from within a cased well by providing an apparatus having a
5 first electrode that electrically engages a first particular
6 section of casing for receiving first voltage related signals
7 at a specific depth within the well; having a second
8 electrode that electrically engages the first particular
9 section of casing for receiving second voltage related
10 signals located a first distance above said first electrode
11 wherein the magnitude of the resistance of the portion of
12 casing between said first and second electrodes is the first
13 resistance; and a third electrode that electrically engages
14 the first particular section of casing for receiving third
15 voltage related signals located a second distance below said
16 first electrode wherein the magnitude of the resistance of
17 the portion of casing between said first and third electrodes
18 is the second resistance. The apparatus also has a fourth
19 electrode that electrically engages the casing at a point
20 located a third distance above said second electrode and a
21 a fifth electrode that electrically engages the casing at a
22 point located a fourth distance above said fourth electrode.
23 The apparatus has means to conduct a first current between
24 said fourth and fifth electrodes, and the fourth distance is
25 chosen such that at least a portion of said first current
26 flows into the formation of interest. The apparatus has
27 means to measure said first resistance and said second
28 resistance. Methods are set forth that include obtaining
29 said first, second, and third voltage related signals while
30 conducting said first current between said fourth and fifth
31 electrodes; determining the magnitudes of said first
32 resistance and said second resistance; and processing the
33 voltage related signals from each of said first, second, and
34

1 third electrodes to provide information useful to determine
2 the resistivity of the geological formation of interest.

3
4 With reference to Figure 14 and related figures, and
5 with further reference to the above disclosure, another
6 embodiment has described a method for providing information
7 useful to determine the resistivity of a geological formation
8 surrounded by borehole casing comprising the steps of causing
9 a first current to flow in a first direction along a
10 predetermined portion of the casing and measuring a plurality
11 of first voltages across said portion of the casing; causing
12 a second current to flow in a first direction along said
13 portion of the casing and measuring a plurality of second
14 voltages across said portion of the casing; and using the
15 first and second voltage measurements to provide information
16 useful to determine the resistivity of a said geological
17 formation. With reference to Figure 14, the term "measuring
18 a plurality of first voltages" means measuring the voltages
19 from electrodes C, D. and E with SW1C connected to electrode
20 B1, and the term "measuring a plurality of second voltages"
21 means measuring the voltages from electrodes C, D, and E with
22 SW1C connected to electrode F. Here, the "first direction"
23 is either up, or down, which may be selected by the settings
24 on the signal generator and the power amplifier.

25
26 With further reference to Figure 14 and other related
27 figures, and with further reference to the above disclosure,
28 another embodiment of the invention describes an apparatus
29 for providing information useful to determine the resistivity
30 of a geological formation surrounded by borehole casing that
31 has a first means to generate and cause a first current to
32 flow in a first direction along a predetermined portion of
33 the casing, a second means to measure a plurality of first
34 voltages across said portion of the casing, a third means to

1 generate and cause a second current to flow in a first
2 direction along said portion of the casing, and a fourth
3 means to measure a plurality of second voltages across said
4 portion of the casing. This apparatus also has processing
5 means using the first and second voltage measurements to
6 provide information useful to determine the resistivity of a
7 said geological formation. With reference to Figure 14, the
8 term "measuring a plurality of first voltages" means
9 measuring the voltages from electrodes C, D. and E with SW1C
10 connected to electrode B1, and the term "measuring a
11 plurality of second voltages" means measuring the voltages
12 from electrodes C, D, and E with SW1C connected to electrode
13 F. Here, the "first direction" is either up, or down, which
14 may be selected by the settings on the signal generator and
15 the power amplifier.

16
17 Many references have been defined herein. In many
18 instances, those references have been actually included in
19 the specification by using the phrase "..., an entire copy of
20 which is included herein by reference." Similar variations
21 of this phrase have been used elsewhere in the specification.
22 To be precise, the phrase "included herein by reference" is
23 also equivalent to the phrase "incorporated herein by
24 reference".

25
26 While the above description contains many specificities,
27 these should not be construed as limitations on the scope of
28 the invention, but rather as exemplification of preferred
29 embodiments thereto. As has been briefly described, there
30 are many possible variations. Accordingly, the scope of the
31 invention should be determined not only by the embodiments
32 illustrated, but by the appended claims and their legal
33 equivalents.